

## The effect of stress distribution and displacement of open subtalar dislocation in using titanium alloy and stainless steel mitkovic external fixator – a finite element analysis

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### Abstract

An external fixator is normally used by medical surgeons in treating subtalar dislocation due to its biomechanical characteristics that can providing an adequate stability, preventing deformity (mal-union and non-union), reduce rate of infections, and promoting fast healing process as compared to conventional internal fixator. Apart from the configurations and fixation techniques, previous studies has mentioned that the stability of external fixator can be altered and manipulated by using different materials, e.g. stainless steel, titanium alloy and polymer. To be noted, the current available research works that have been investigated on different materials of external fixator are still lacking, therefore, the present study is aims to conduct related study. The main objective of the research work is to simulate finite element model of foot and ankle joint associated with open subtalar dislocation in which treated with Mitkovic external fixator by using two different material properties; titanium alloy (Model 1) and stainless steel (Model 2). The three-dimensional model of foot and ankle joint were reconstructed using images of CT dataset. For the soft tissues, cartilages at the ankle joint were developed by offsetting the bone surfaces with 1 mm thickness while ligaments were modelled with linear links. Homogeneous and isotropic properties were assigned to the bone, Mooney-Rivlin model for cartilage and specific stiffness value for ligaments. In order to simulate stance phase during walking condition, an axial load of 350 N was applied to the proximal tibia bone. The results of von Mises stress demonstrated that Model 2 has a low magnitude (127 MPa) at the pin-bone interface of tibia bone, compared with Model 1 (369 MPa). As for the local displacement at the bony segment of fibula, Model 2 (3.3 mm) indicated high stability of the external fixator than Model 1 (7.4 mm). In conclusion, the use of stainless steel material for Mitkovic external fixator can provide adequate stability and optimum stress distribution.

**Keywords:** Finite element, biomechanics, ankle dislocations, mitkovic external fixator, micromovement

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## INTRODUCTION

Foot and ankle joint are located at the lower limb of a human body. The anatomy of the ankle foot is a complex joint construct as compared with other joints such as hip, elbow and knee. The common ankle injuries are associated with bone dislocations and fractures (Anwar, Tuson, & Khan, 2008; Bartolozzi & Lavini, 2004). The most injuries to the ankle joint is subtalar dislocations (Jerome *et al.*, 2008). One of them is open subtalar dislocation, in which can be defined as open injuries where the ligaments at the lateral side of ankle are torn. Previous scholar (Golner *et al.*, 1995) categorised it into four types; medial, lateral, posterior and anterior. The medial dislocations are the most common injuries where it is normally caused by the lateral

displacement of the talus responding to an applied inversion force to the plantarflexed foot (Harris *et al.*, 2008). Due to excessive force exerted to the foot, this causing the subtalar joint be disrupted, particularly to the lateral ligament to be torn.

After a surgery, the medical surgeons do not allow patients to stand and walk (Ansah & Sella, 2000; Harris *et al.*, 2008). However, this may causes in complications such as mal-union, non-union and deep vein thrombosis due to prolonged immobilization period (Hyder *et al.*, 1997; Jerome *et al.*, 2008). Therefore, a special device should be used to prevent the complications so that the patients could having fast healing procees to the injuries. The use of a medical device, called external fixator as a treatment of subtalar dislocation is popular amongst surgeons (Milenkovic *et al.*, 2006; Mitkovic *et al.*, 2005).

This device can prevent complication such as infections, deformities and loss of reduction. In treating subtalar dislocations, many medical experts disallow full weight bearing for patients after a surgery (Harris et al., 2008). However, this may cause in prolonged immobilization which can lead to deep vein thrombosis. Thus, the external fixator is introduced since this device allows the early mobilization of patients and preventing complications while supporting the ankle joint for ligament healing (Ansah & Sella, 2000). To dated, apart from other conventional constructs, the Mitkovic external fixator has become the most popular construct for treating open subtalar dislocations (Ansah & Sella, 2000; Milenkovic et al., 2006). This construct is based on unilateral external fixator with a system that provide three-dimensional freedom where the pin placement should be fixed to the bone without the need of a special guide (Mitkovic et al., 2005; Mitkovic et al., 2005). As compared with other configurations of external fixator, the high flexibility of the uniplanar frame allows for one type of the frame to be converted into another during the intervention and from a rigid to a dynamic one without changing the position of the pins (Marsh et al., 1991).

For treating open subtalar dislocation, stability of fixation and ankle joint is one of the main factors to ligament healing (Carroll & Koman, 2010; Golner et al., 1995). The fastest healing time for open subtalar dislocation injuries that treated with the external fixator was 5 weeks from the first surgery (Ansah & Sella, 2000). The stability of external fixator can be demonstrated by applying a proper material (Carrigan, Whiteside, Pichora, & Small, 2003). Additionally, wrong selection of material can increase stresses and displacement at the pin-bone interface and distal fibula, respectively, thus can increase rate of infections to the patients. The main function of the Mitkovic external fixator with different material properties has never been demonstrated in the literature. Therefore, there are two objectives of the present study; (1) to reconstruct three-dimensional ankle subtalar dislocation fixated with two different materials (stainless steel and titanium alloy) of Mitkovic external fixator and (2) to investigate the effect of stress and displacement during the stance phase of a gait cycle via finite element method. The results presented here could be used by medical surgeons and other researchers to justify the choices of suitable material used for external fixator.

## MATERIALS AND METHODS

### Development of ankle and foot bones

The present study used previous CT data images (Izaha et al., 2012) (slice thickness of 1.5mm in a 512 x 512 matrix) of healthy person to reconstruct the three-dimensional (3D) model of eight bones which include metatarsals, cuneiforms, navicular, cuboid, calcaneus, talus, fibula and tibia bone (Aarnes et al., 2006). The CT images of the right lower limb of a healthy volunteer (a 21 years old male) were used to differentiate two segments of bone, cortical and cancellous, by setting a threshold value of 700 (Yosibash et al., 2007). The value more than 700 was for cortical and less than 700 was for cancellous bone. A manual segmentation process was carried out using 'edit masks' tool in which to erase and draw the slices of images. The segmentation process continued with calculating 2D images into 3D model. An inspection process of the contact bone was carried out in order to provide adequate distance between the different bones by subtracting each body via Boolean operations. For a region of interest, the tibia and fibula were cut approximately 20 cm above the medial tibia malleolus (Ramlee et al., 2013, 2014; Wang et al., 1995). The region of interest is acceptable as mentioned and used by previous scholars (Cheung et al., 2006; Wang et al., 1995). The 3D model of bones were saved in STL file for further pre-processing method. All of these steps were performed in Mimics 15.1 software (Materialise, Belgium). The flowchart of the development of 3D model of bone is as shown in Figure 1.

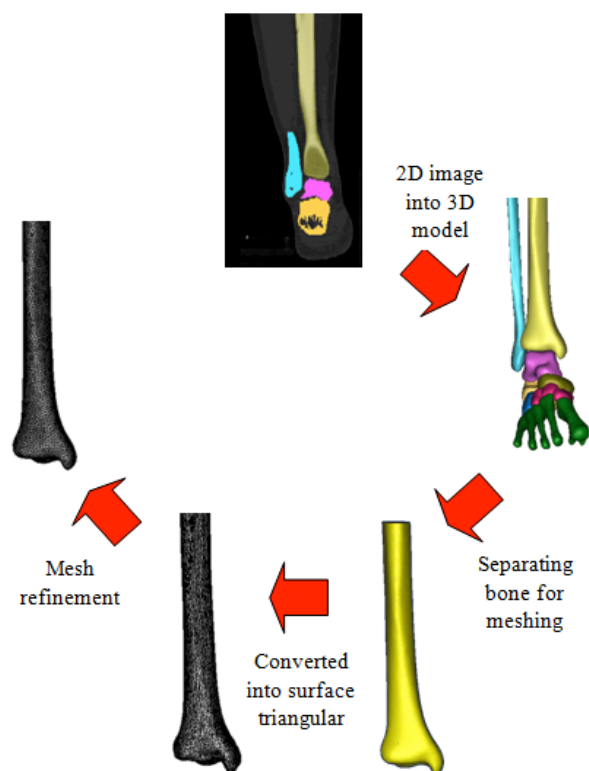


Figure 1 The steps to reconstruct 3D model of bone

### Development of soft tissues

For the ankle joint that consisted with many soft tissues, a proper methodology was conducted to construct 3D model of articular cartilages surrounding the joint. Articular surfaces of bones were extruded out with a uniform size of 1 mm (Cheung et al., 2006). As the authors using the same CT images, the same segmentation method as the development of bone was performed. Therefore, the 3D model of cartilage for calcaneus, talus, fibula and tibia were constructed via manual segmentation process (Carrigan et al., 2003). This includes using Boolean operations in Mimics software to check whether there is any intersection between two different cartilages at a bone joint. The boundary and geometry of the selected cartilages were based on previous studies (Akiyama et al., 2012; Millington et al., 2007). In the beginning of process, the extruded surface consisted of one layer only, then the second layer was constructed by offsetting the first layer with a value of 1 mm thickness. Some modifications were conducted due to the intersection between two rigid bodies of cartilage and this was repeated until the intersecting numbers become zero. To be noticed, there is no development of other cartilages around the forefoot and midfoot in the present study due to the fact that only small magnitude of load transfers to the foot joint during a normal gait cycle (Calhoun et al., 1994; Haraguchi et al., 2009). For the material properties, the cartilages were assigned with Mooney-Rivlin hyperelastic behaviour with coefficients of  $C_{01}=0.41$  MPa and  $C_{10}=4.1$  MPa (Bajuri et al., 2012; Ramlee et al., 2013).

The complexity of the ankle and foot joint model (Figure 3) came with thirty-seven ligaments surrounding the tissue. Two points were chosen in two different bones via a method of node-to-node to construct the ligaments. The ligaments were modelled using linear link elements and the stiffness value were set ranging from 40 to 400 N/mm as shown in Table 1 (Aarnes et al., 2006; Beumar, Van Hemert et al., 2003; Iaquinio & Wayne, 2010; P. C. Liacouras & J.S. Wayne, 2007; H. Pfaeffle et al., 1996; Siegler et al., 1988). In order to mimicking real geometrical conditions of ankle, multiple parallel links were utilised for better distributing the load from origin to another points. The positions of ligaments were based on an anatomy book and confirmed by a medical expert (Netter, 2003). All steps in developing the ligaments were performed through a finite element software, Marc.Mentat.

**Table 1** Stiffness of the ligaments

Ligaments represented in the models	Stiffness(N/mm)
Interosseous membrane (4 ligaments)	400 (H. J. Pfaeffle et al., 1996)
Anterior tibiofibular (distal)	78
Posterior tibiofibular (distal)	101
Anterior talofibular	90
Posterior talofibular	70 (P.C. Liacouras & J.S. Wayne, 2007)
Calcaneofibular	70
Anterior tibiotalar	70
Posterior tibiotalar	80
Tibiocalcaneal	122
Tibionavicular	40
Interosseous talocalcaneal	70
Lateral talocalcaneal	70
Medial talocalcaneal	70
Posterior talocalcaneal	70
Dorsal talonavicular (2 ligaments)	70
Calcaneonavicular (dorsal & plantar)	70
Calcaecuboid (dorsal & short plantar)	70
Cuboideonavicular (dorsal & plantar)	70
Cuneonavicular (dorsal & plantar)	70
Intercuneiform (dorsal & plantar)	70
Tarsometatarsal (dorsal & plantar)	70
Metatarsal (dorsal & plantar)	70
Medial plantar fascia	200
Central plantar fascia	230
Lateral plantar fascia	180
Long plantar	70

### Modelling of Open Subtalar Dislocation

Previous studies mentioned that lateral collateral ligaments were ruptured when patients suffered open subtalar dislocation (D'Anca & A.F., 1971; Fahey et al., 1965; Haines, 1939). Therefore, the open subtalar dislocation was simulated with an assumption of unexisted ligaments at the lateral collateral side (D'Anca & A.F., 1971; Daruwella, 1974; Fahey et al., 1965; Sloane & Coutts, 1937). These ligaments are the calcaneofibular, posterior talofibular and anterior talofibular (Figure 3).

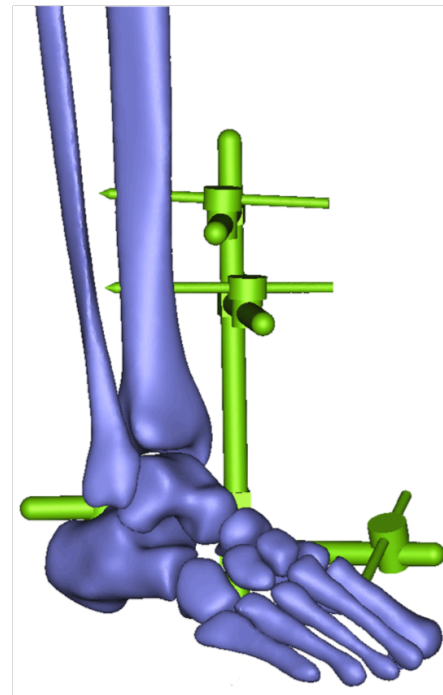
### Development of External Fixator

The Mitkovic external fixator was modelled and designed via three-dimensional computer aided design software, Solidworks software (Dassault, USA) with rods and pins size of 11 mm and 5 mm, respectively. The dimensions of external fixator were referred to the available commercial product from Mitkovic as well as previous literature works (Ansah & Sella, 2000; Mitkovic et al., 2005; Mitkovic et al., 2005). The fixator were then meshed with linear first order tetrahedral elements using 3-Matic 7.1 (Materialise, Belgium). Two pins were fixated at the tibia, one at the calcaneus and another pin at the first metatarsal bone to represent the Mitkovic construct as shown in Figure 2.

### Finite Element Modelling

All STL files were then imported into Marc.Mentat (MSC.Software, USA) in order to convert the 3D model into linear first tetrahedral elements (Figure 3). A properties of 7300 MPa and Poisson's ration of 0.3 (Nakamura et al., 1981) were assigned to the cortical bone while the material properties of cancellous bone were set to 1100 MPa and 0.3 (Kim, Kim, & Chang, 2011). In the present study, two different material properties of external fixator were used; Model 1 was developed using the Mitkovic titanium alloy and Model 2 was developed using the Mitkovic stainless steel. These two models have Young's modulus of 110,000 MPa (Benli et al., 2008) and

200,000 MPa (Vasquez, Pedersen, Lidgren, & Taylor, 2003), respectively. Convergence study was conducted in the previous study (Ramlee et al., 2014a) and the findings showed that optimum mesh size for the bone was 3 mm and the external fixator was 1 mm.



**Figure 2** Three-Dimensional model of ankle and foot bone fixated with Mitkovic external fixator

### Boundary Conditions

An axial load was applied to the proximal tibia bone. The load was based on a force taken from the gastrocnemius and soleus muscles during stance phase. During the stance phase of a gait cycle, 50% of the body weight was generated (Cheung et al., 2005; Simkin, 1982). In the present study, 350 N was applied based on the subject's body weight of 70 kg. For preventing a movement of the rigid body during the simulated condition, all metatarsals and calcaneus bone were fixed.

## RESULTS AND DISCUSSION

### Von Mises Stress

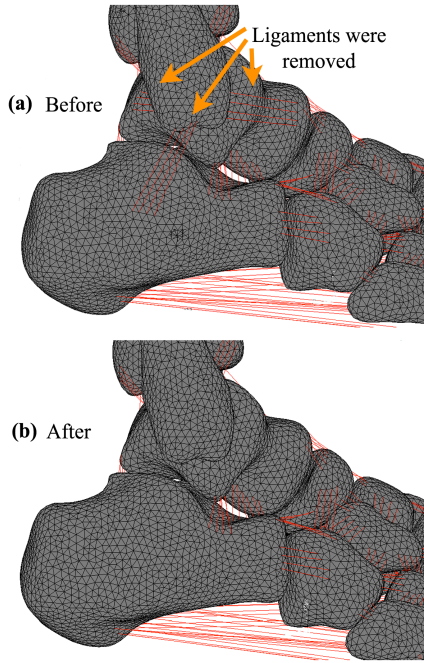
Figure 5 shows the contour plots of von Mises stress at the pin-bone interface for tibia, calcaneus and metatarsal bone during the stance phase of a gait cycle. The maximum stress at Model 1 (369 MPa) is greater than Model 2 (127 MPa) with at least 90% difference between both model at the second cortex of pin-bone interface. For the calcaneus bone, Model 1 (683 MPa) produced at least 2.9 times greater stress compared to Model 2 (262 MPa). On the other hand, the von Mises stress at the pin-bone interface of metatarsal bone for Model 1 (591 MPa) demonstrated larger magnitude than Model 2 (245 MPa), with 82% difference between both models. In this study, the stress concentrated at the pin-bone interface was in agreement with previous studies (Brianza et al., 2011; Donaldson et al., 2012). The high stresses at this critical local point supported the decision made by medical surgeons for disallowing patients to experience full weight bearing in clinical practice (Ansah & Sella, 2000; Dlimi et al., 2011; Harris et al., 2008). It is crucial to note that a normal bone can sustain an axial load until the ultimate strength of 193 MPa (Pinner & Sangeorzan, 2001). Based on the results of the von Mises stress in the present study, it is not recommended for patients to walk and stand during treatment period.

Contour plots of von Mises stress of external fixators with difference material properties from numerical simulation are shown in

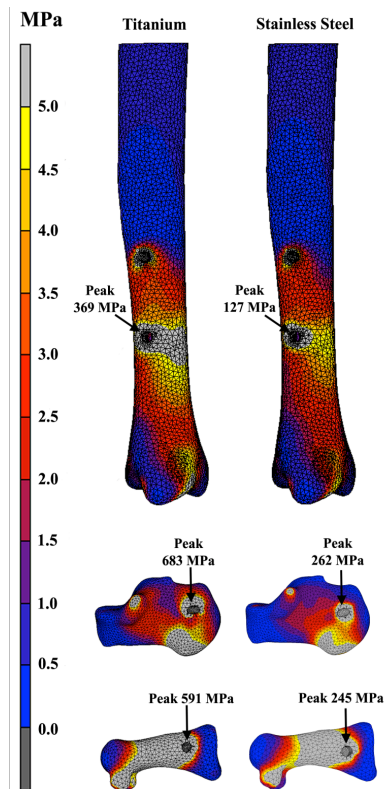
Figure 5. The stress concentrated more in Model 2 (524 MPa) at the calcaneus pin as compared to Model 1 (486 MPa). However, these peak values are still below the ultimate strength of titanium alloy (500-600 MPa) and stainless steel (800-900 MPa)(Gorsse & Miracle, 2003; Hyde *et al.*, 2010). From another view, the stress is also distributed at connecting bar, tibia pin and first metatarsal pin. Nevertheless, the stresses surrounding external fixator were below the peak values, which indicates that the Mitkovic frame is safe to be used for treating this particular pathological problem.

**Displacement**

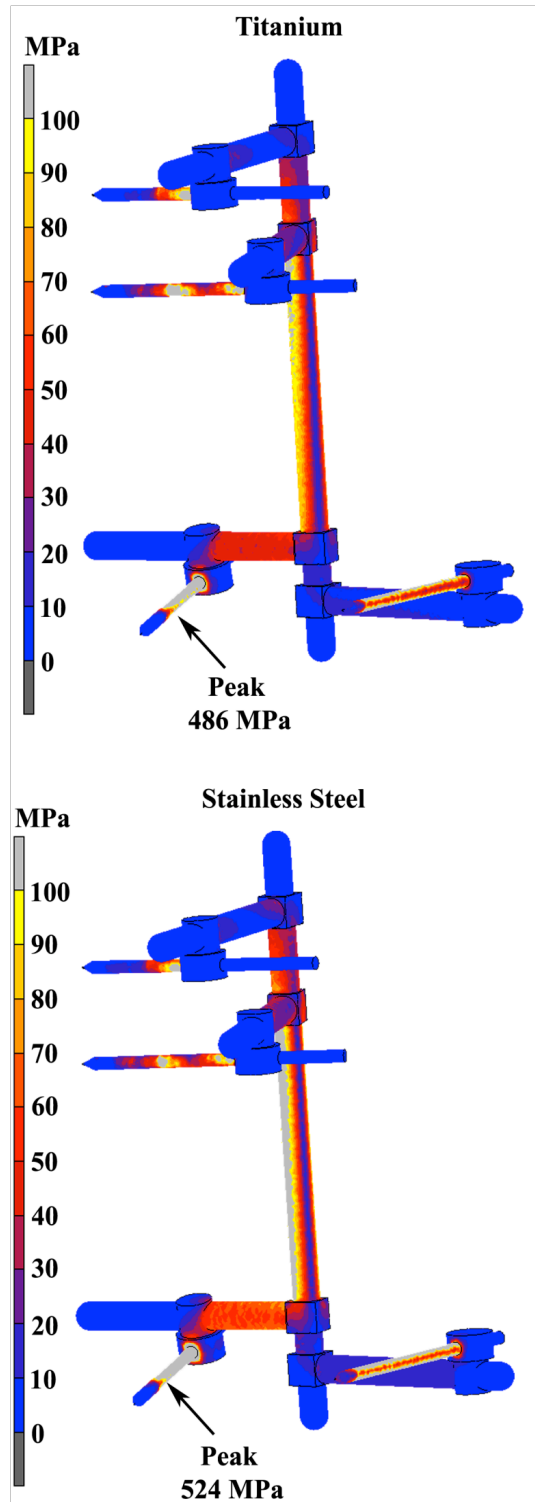
Local displacement at the bony segments that are connected by calcaneofibular ligament as shown in Figure 6. Model 1 with material of titanium alloy demonstrated higher displacement of 7.4 mm as compared to Model 2 (3.3 mm). To be noted, the stability of the bone affected the healing process of ligaments. With higher magnitude of displacement, a time taken for ligaments to heal will be longer. Previous studies demonstrated the same situation where the smaller displacement at the bony segment of ankle joint can minimize the time taken remove external fixator (Ansah & Sella, 2000; Golner *et al.*, 1995; Ramlee *et al.*, 2014a; Ramlee *et al.*, 2014b).



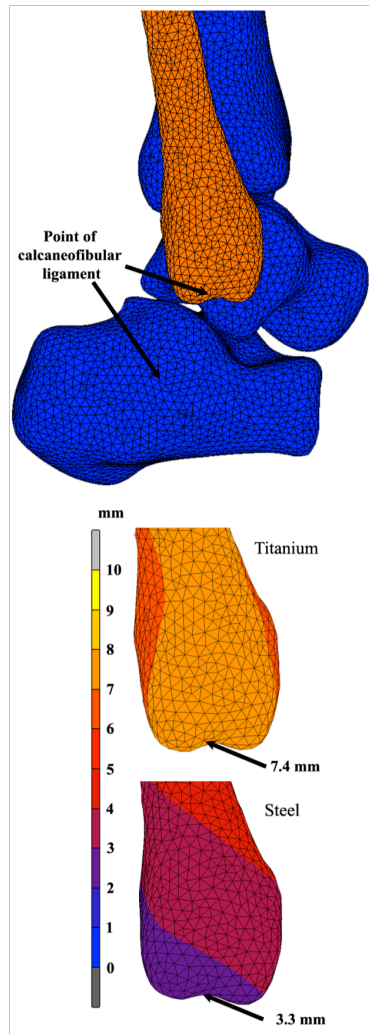
**Figure 3** Finite element model showing the ligaments were removed to simulate open subtalar dislocation



**Figure 4** Von Mises stress at the pin-bone interface



**Figure 5** Contour plots of von Mises stress of Mitkovic external fixator



**Figure 6** Contour plots of displacement at the local point of calcaneofibular ligaments

External fixator is a favourable option for the management of open subtalar dislocation due to its minimally invasive property, able to provide adequate stabilization and less infection (Pinner & Sangeorzan, 2001; Seibert *et al.*, 2003). Many scholars proved that stable fixation can hasten soft tissue healing during a treatment (Chandran *et al.*, 2006; Seibert *et al.*, 2003). A proper strategy should be taken properly by medical surgeons before a surgery can be made. One of the strategy is the selection of material of external fixator. Inability to provide a stable construct due to improper selection of material is the major cause of post surgery complications such as malunion, non-union, and secondary fracture at the pin-bone interface (Inokuchi *et al.*, 1996; Vasquez *et al.*, 2004). Based on the results from Figure 4, the secondary fracture could be happened at the pin-bone interface of tibia, calcaneus and first metatarsal bone if the medical doctors allowing the patients to walk and stand during the treatment period.

Several assumptions and limitations were considered in the present study where these cannot be avoided when dealing with computational simulation. First, the geometrical condition of open subtalar dislocation was simplified and followed a normal patient condition. Though the dislocation can cause talus or calcaneus bone to be displaced from original position, however, the effect of these bones can only be simulated by using high resources of computer as well as CT data images from real patients. Nevertheless, the simulated of open dislocation and fracture bone were demonstrated by previous studies with an acceptable outcomes (Benli *et al.*, 2008; Brianza *et al.*, 2011; Ezquerro *et al.*, 2007; Izaham *et al.*, 2012). The second limitations of the study was the assumption of linear isotropic and homogenous for both cortical and cancellous bone. To be noted, this

limitation and assumption were normally used by the biomedical engineers and researcher to simulate the bone properties via finite element method (Izaham *et al.*, 2012; P. C. Liacouras & J. S. Wayne, 2007; Liu & Zhang, 2013). Therefore, it is recommended that future investigation can be performed using greyscale value of CT images to mimick real material properties of the bone.

Another limitation in this study is the axial loading. A force value applied at the proximal tibia was simulated from Achilles tendon force during the stance phase of a gait cycle (Simkin, 1982), while the other structural muscles such as longus and brevis were not considered in this study due to its low magnitude of forces. In addition, the thickness of cartilages was another assumption where a uniform thickness of 1 mm were applied only for tibia, fibula, calcaneus and talus bone (Ramlee *et al.*, 2014a). The rest of cartilages around foot should be constructed in the future studies where this could influence the simulated results.

## CONCLUSION

The present study simulated finite element model of open subtalar dislocation treated with Mitkovic external fixator with two different materials; titanium alloy and stainless steel. As compared with titanium alloy, the results obtained in terms of stress and displacement demonstrated that stainless steel material for the external fixator can provide adequate stability to the bony fragment as well as optimum stress surrounding bone tissue. However, extra care should be considered when allowing patients to walk and stand during the treatment to avoid complications especially secondary fracture at the pin-bone interface.

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